Low-Threshold Noble Element Detectors - Executive Summary (~1 Page)

G. Giovanetti, A. Kopec, K. Ni, C. Savarese, S. Westerdale, J. Xu

Noble element detectors have great potential to search for new physics through the direct detection of light dark matter, reactor neutrinos, and natural (e.g. solar) neutrinos. Noble element detectors that are sensitive to single ionization electrons via electroluminescence are able to detect low energy O(10 eV) electronic recoils and O(100 eV) nuclear recoils, although without nuclear and electronic recoil discrimination. Two-phase argon and xenon detectors are well-developed for heavy WIMP searches, but their signal production mechanisms and backgrounds below O(keV) need further investigation. Liquid neon deserves further investigation, with its intrinsic radiopurity and favorable kinematics for recoil energy transfer from light dark matter and low energy neutrinos. A new class of compact O(100 kg) low-threshold (sub-keV) noble element detectors will offer complementary physics opportunities to large (100 tonne) noble liquid detectors in dark matter and neutrino physics, while being competitive with other low-threshold detector technologies that are more difficult to scale up in target mass.

Without nuclear and electronic recoil discrimination, systematic backgrounds and radioactivity obscure typically background-free nuclear recoil event searches. It is necessary to select the most radiopure materials, particularly photosensors. Better liquid or gas purification techniques (e.g. cryogenic distillation) drastically reduce beta and gamma backgrounds stemming from ^{3}H, ^{39}Ar, ^{85}Kr, and the $^{220,222}Rn$ decay chains. Cosmogenic activation rates must be further studied and considered for handling detector materials above ground. Beyond particle interaction backgrounds, high rates of single- and few-electron signals are observed. Such spurious electrons have defied clear explanation and appear related to charge buildup on surfaces or in unknown chemical interactions,among other potential effects [3,5,7,12,13,34]. Dedicated R&D is needed to better understand the sources of these backgrounds and develop mitigation techniques. Fast and efficient gas purification, liquid purification technologies, cleaner alternative detector materials, and various electric field configurations must be explored to optimize signal measurement efficiency and reduce backgrounds. Electroluminescence in a single-phase noble element detector, either high-pressure gas or liquid, offers a thermodynamically simpler possibility for single-electron detection, without the hypothesized electron-trapping at the liquid-gas interface in two-phase LXe detectors.

Most noble element detectors searching for heavy WIMPs rely on in-situ calibrations for electronic and nuclear recoils in order to reliably reconstruct events' energies[25,26,27,28]. A number of ancillary external calibration campaigns [29,30] refine the scintillation and ionization yields of liquid argon and liquid xenon, and explore the responses of other noble elements at the relevant low energies. In the search for low mass dark matter and solar and reactor neutrinos with CEvNS, a substantial effort to identify electronic and nuclear recoil calibration sources is needed to validate sensitivity below O(keV)[33]. The Migdal effect, expected in this energy region, has yet to be conclusively observed [31]. Its key experimental confirmation will support the use of this channel to access lower energy dark matter interactions [32].

While current dark matter and neutrino experiments have focused on pure, noble liquid targets (e.g argon and xenon), there is a significant interest in exploring the effects of doping liquid argon with xenon and other elements [14–24]. These dopants are typically chosen for ease of light detection and increasing scintillation and ionization yields. At higher concentrations, dopants can also be favorable targets in their own right. For example, hydrogen or hydrogenous compounds doped in liquid xenon provide a light nucleus with more efficient kinematic coupling to light dark matter, and nuclei with an odd number of nucleons can add spin-dependent sensitivity. Further research is needed to develop the capacity for stable, high-purity doping and to measure the effects on low-energy nuclear and electronic recoils for dark matter and neutrino detection.

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Executive Summary (~1 page)

The goal is to build low-threshold noble liquid or high pressure noble gas detectors to search for new physics through direct detections of light dark matter, reactor neutrinos, and natural neutrinos.

[Quantitative description of targets]
Noble element detectors that are sensitive to single ionization electrons through electroluminescence have the capability to detect low energy O(10 eV) electronic recoils and O(100 eV) nuclear recoils. This opens up opportunities to search for new physics through light dark matter and low energy neutrinos from either artificial sources, e.g. reactors, or natural sources, such as the Sun. Two-phase argon and xenon detectors are well developed for the heavy WIMP searches, while their background and signal production below keV threshold need further investigation. Liquid neon and helium detectors using the two lighter noble elements are much less developed despite their intrinsic cleanliness in radiopurity and favorable kinematics in recoil energy transfer. In addition, electroluminescence production in liquid phase or in high-pressure noble gases offer another possibility for the single electron detection without the complication and possible electron-trapping of the liquid-gas interface in two-phase detectors. A new class of small yet modest (100kg to 1 tonne) low-threshold (sub-keV) noble element detectors will offer complementary physics opportunities to large (100 tonne) noble liquid detectors in dark matter and neutrino physics while be competitive to other low-threshold detector technologies that are more difficult to scale up in target mass.

[Backgrounds - Main focus: Spurious electron backgrounds]
[One sentence on ERs]

Without nuclear and electronic recoil discrimination, systematic backgrounds and radioactive impurities obscure typically background-free nuclear recoil event searches. Improvements can be made by selecting the most radiopure materials, with particular attention paid to photosensors. Better purification techniques, such as cryogenic distillation, drastically reduce beta and gamma backgrounds stemming from ^{3}H, ^{39}Ar, ^{85}Kr, and the $^{220,222}Rn$ decay chains. Cosmogenic activation rates must be studied and considered for building, storing, and transporting detector materials above ground. Beyond particle interaction backgrounds, high rates of single- and few-electron signals are strongly correlated in time and location to prior energetic interactions. Research and development efforts toward improved purity, through either fast and efficient gas purification or liquid purification technologies, and optimized electric fields are still needed to mitigate this crippling detector background. Such spurious electrons have defied clear explanation and appear related to charge buildup or a specific electronegative impurity species [3,5,7,12,13]. Minimizing detector and radioactivity backgrounds are essential to lowering the background near the threshold to study neutrinos and searching for dark matter.
Abby

[Lowering threshold: Main focus Low-energy calibration]
[One sentence on tuning E-field]
Most of noble element detectors operated to search for heavy WIMPs rely on in-situ calibrations both for electronic and nuclear recoils in order to reliably reconstruct events' energy scale while minimizing systematic effects [25,26,27,28]. A number of ancillary external calibration campaigns [29,30, any recent one?] allowed to refine the scintillation and ionization yields of LAr and LXe at the relevant energies. On the contrary, in the search for low mass dark matter uncertainties in low-energy electronic and nuclear recoil charge yields are still significant, thus limiting the current sensitivity for particles below a few GeV/c^2. A substantial effort aimed at producing reliable ex-situ sub-keV ER and NR calibrations for noble element targets is needed. Furthermore, by exploiting the very same measurement campaigns, it is also important to observe the Migdal effect [31]. This key experimental confirmation will support the use of this channel to access new swaths of the parameter space at even lower masses [32].
In the perspective of developing dedicated experiments searching for new physics at extremely low energies, the electric field configuration of such detectors will have to be optimized for S2-only analyses, thus requiring ex situ calibrations at variable fields.
Claudio

[Doping]
While most noble liquid detectors used in current dark matter and neutrino experiments have focused on pure targets, largely LAr and LXe, there is a significant body of literature exploring the effects of doping LAr with Xe [14–19], allene [20–22], tetra-methyl-germanium [23], trimethylamene [24], and triethylamene [24]. These dopants are typically explored in the context of wavelength shifting and increasing scintillation and ionization yields. In low-threshold detectors, these properties may enable LAr to forego the use of other wavelength shifters, and increasing the scintillation and ionization yield, particularly for nuclear recoils, essentially by allowing energy that would otherwise be lost as heat to convert to visible modes. At higher concentrations, dopants can also add targets with favorable targets. For example, H provides a

light nucleus with more efficient kinematic coupling to light dark matter, and odd-A nuclei can add spin-dependent sensitivity. Similar ideas are being explored for doping LXe with hydrogenous compounds. R&D is needed to develop the capacity for stable, high-purity doping and to measure the effects on low-energy nuclear and electronic recoils.
Shawn

Instrumentation requirements to achieve physics goals (list)

To achieve the physical goals, it is necessary to

1. Develop noble liquid TPCs for electron-counting (S2-only) analyses
    a. Using LAr, LXe, and LNe
    b. Explore doped noble liquid TPCs, such as LAr+Xe, and other options
2. Achieve low energy thresholds, targeting scale of target’s ionization energy: O(10 eVee)
3. Decrease backgrounds (see Figure 1)
    a. Need approximately <1 events/kg/day with 0.5-keVnr threshold for reactor neutrinos
    b. Need O(10^3 events/keVnr/ton/year) for ^{8}B solar neutrinos
    c. Add some quantitative figure for backgrounds needs for DM
4. Develop high-granularity and single-PE sensitive photosensors to detect S2 light
5. Require stable high voltage and electrodes system
6. Must achieve high liquid purity to maximize electron collection efficiency and minimize spurious electron backgrounds

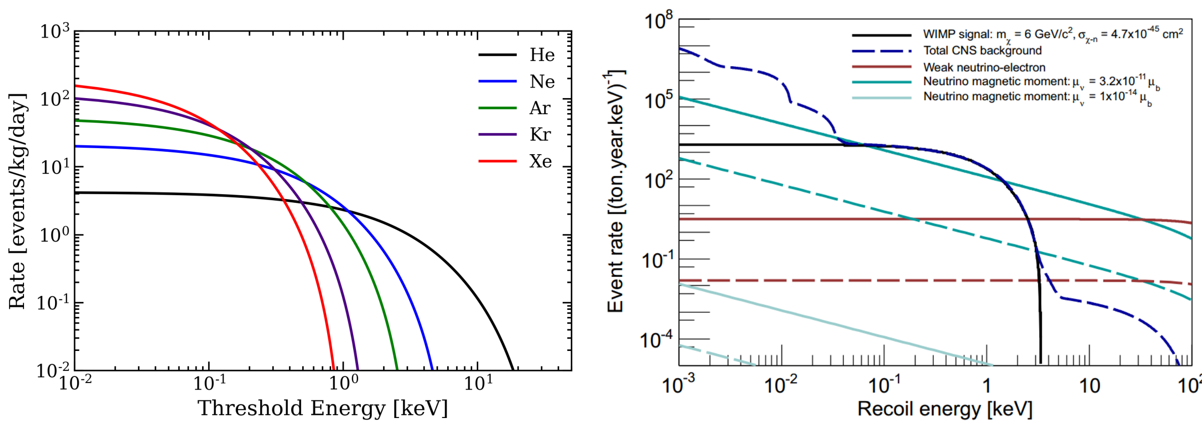

Figure 1. (Left) Integrated CEvNS rate above threshold with 6×10^{12} neutrino/cm^2/s (25 m from 3 GW_{th} reactor) [9]. (Right) Neutrino backgrounds in a LXe dark matter experiment, compared with a 6 GeV/c^2 WIMP spectrum [PRD 89, 023524 (2014)]

Significant instrumentation challenges (list)

Instrumentation challenges fall into two categories, regarding lower thresholds and decreasing backgrounds. These are as follows:

1. Decrease low-energy backgrounds

    a. Spurious electron backgrounds (chemical impurities, photo-ionization, charge build-up)
        i. Not well-understood. R&D is needed to characterize SEs and understand their full phenomenology
        ii. Many are likely caused by chemical impurities, which can be reduced with improved purification, including in situ liquid-phase purification
        iii. In LXe, charge build-up also appears to be a significant source. This can be reduced by Optimizing the electric field to reduce charge accumulation at liquid surface
    b. Electronic recoils (no electronic/nuclear recoil discrimination)
        i. Internal β emitters like ^{3}H, ^{39}Ar, ^{85}Kr, ^{220,222}Rn decay chains can be reduced with improved isotopic purification
        ii. γ-emitters in detector components must be reduced with more radiopure photosensor development
        iii. They can also be produced by cosmogenic nuclides, for which we need to better understand cosmogenic activation rates
2. Lowering thresholds
    a. Uncertainties in low-energy electronic and nuclear recoil charge yields require ex situ calibration
        i. It is also important to observations the Migdal effect to support its use in low-mass DM analyses
    b. Electric fields should be optimized for S2-only analyses, requiring ex situ calibration at variable fields
    c. Doping (low-ionization energy dopants for higher charge yields, low-A targets for higher-energy nuclear recoils) may improve the sensitivity of low-threshold detectors
        i. Need high purity and stability doping techniques, which requires R&D
        ii. Ex situ calibration studies with doping are needed to study effects on of doping on the TPC's response

Relevant physics areas

1. Low-mass dark matter with 1 MeV–10 GeV masses through recoil channels
    a. Dark matter with nuclear and electronic couplings
2. Light dark matter with 10 eV–1 keV masses through absorption channels
    a. Axion-like particles and hidden photons
3. Measurements of CEvNS from artificial neutrino sources (Reactors)
    a. Sterile neutrino searches with short baselines
    b. Non-standard neutrino interactions and new boson mediators
    c. Neutrino magnetic moment
    d. Neutron distribution in nucleus (input to nuclear equations of state)
    e. Weak mixing angle
4. Measurements of CEvNS from natural neutrino sources
    a. Supernova neutrinos

b. Solar neutrino measurements (mostly ^{8}B neutrinos)

Relevant cross-connections

1. CF01 WP2: “The landscape of low threshold detection in the next decade”
2. CF01 WP3: “Calibrations and Backgrounds for Direct Detection”
3. NF white paper on CEvNS measurements